# Measurements of the UV Upturn in Local and Intermediate-Redshift Ellipticals

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**Abstract.**

The rest-frame ultraviolet contains the most sensitive indicators of age for elliptical galaxies. While the near-UV flux from young ellipticals isolates the main sequence turnoff, the far-UV flux in old ellipticals is dominated by hot horizontal branch (HB) stars. This evolved population was first revealed by early UV observations showing a sharp flux increase shortward of rest-frame 2500 Å, subsequently dubbed the "UV upturn." The phenomenon has since been characterized in many local ellipticals, and measurements at intermediate redshifts are now underway. Once ellipticals reach ages of 5–10 Gyr, stellar and galactic evolution theories predict that the UV-to-optical flux ratio can increase by orders of magnitude over timescales of a few Gyr, making the UV upturn the most rapidly evolving feature of these galaxies. It is thus expected to fade dramatically with increasing redshift.

I review the imaging and spectroscopic evidence for the nature of the UV upturn in nearby ellipticals, and then present observations that measure the UV upturn at an epoch significantly earlier than our own. Far-UV data from the Hopkins Ultraviolet Telescope demonstrate that the spectra of nearby ellipticals are dominated by hot HB stars. Faint Object Camera UV imaging of M32 and the M31 bulge detected the UV-bright phases of post-HB stars, but did not reach the HB itself. Recent Space Telescope Imaging Spectrograph observations were the first to image the hot HB and post-HB stars in the center of the nearest elliptical galaxy, M32; these observations also show a striking lack of UV-bright post-AGB stars. Faint Object Camera observations of Abell 370, a rich galaxy cluster at $z = 0.375$, show that giant ellipticals at a lookback time of 4 Gyr can exhibit strong UV luminosity, with no evidence of evolution in the UV upturn between this epoch and our own, thus implying a high redshift of formation ($z_f \geq 4$).

## 1. Introduction

The UV upturn is a sharp rise in the spectra of elliptical galaxies and spiral bulges shortward of rest-frame 2700 Å. Also known as the "UV rising branch" or the "UV excess," it was discovered with the OAO-2 satellite (Code 1969). Prior to this discovery, we did not expect such a UV-bright component to these old, passively-evolving populations. Many candidates were suggested to explain the upturn, including young massive stars, hot white dwarfs, hot horizontal branch (HB) and post-HB stars, and non-thermal activity (see Greggio & Renzini 1990 for a complete review). As the measurements of local ellipticals were expanded with IUE, another surprise was the large variation in the strength of the UV upturn from galaxy to galaxy, even though the spectra of ellipticals appear very similar at longer wavelengths. Characterized by the $1550 - V$ color, the UV upturn becomes stronger and bluer as the metallicity (optical $\mathrm{Mg}_2$ index) of the galaxy increases, while other colors become redder (Burstein et al. 1988)

Today, it is widely believed that HB stars and their progeny are responsible for the far-UV emission in elliptical galaxies. There are three classes of post-HB evolution, each evolving from a different range of effective temperature on the zero-age HB. On the red end of the HB, stars will evolve up the asymptotic giant branch (AGB), undergo thermal pulses, evolve as bright post-AGB stars to hotter temperatures, possibly form planetary nebulae, and eventually descend the white dwarf (WD) cooling curve. At hotter temperatures (and lower envelope masses) on the HB, stars will follow post-early AGB evolution: they evolve up the AGB, but leave the AGB before the thermal pulsing phase, continue to high temperatures at high luminosity, and descend the WD cooling curve. For the blue extreme of the HB, stars with very little envelope mass will follow AGB-Manqué evolution, evolving directly to hotter temperatures and brighter luminosities without ever ascending the AGB, and finally descending the WD cooling curve. These three classes of post-HB behavior have very different lifetimes, in the sense that the post-AGB stars are bright in the UV for a brief period ($\sim 10^3 - 10^4$ yr), the post-early AGB stars are UV-bright for a longer period ($\sim 10^4 - 10^5$ yr), and the AGB-Manqué stars are UV-bright for very long periods ($\sim 10^6 - 10^7$ yr). The HB phase itself lasts $\sim 10^8$ yr, and so the presence of hot HB stars in a population, combined with the long-lived luminous post-HB phases, gives rise to the strong UV upturn seen in the most massive, metal-rich ellipticals (see Dorman, O'Connell, & Rood 1995 and references therein). A more significant fraction of the far-UV flux from galaxies with a weak UV upturn can theoretically come from post-AGB stars, and in the weakest UV upturn galaxies (e.g., M32), the spectra alone do not require the presence of a hot HB.

The zero age HB (ZAHB) is not only a sequence in effective temperature: it is also a sequence in mass (see Dorman, Rood, & O'Connell 1993). For $\mathrm{T}_{\mathrm{eff}} \gtrsim 6000$ K, a small change in envelope mass ($\lesssim 0.1\ M_\odot$) corresponds to a large change in $\mathrm{T}_{\mathrm{eff}}$ ($\Delta\mathrm{T}_{\mathrm{eff}} \gtrsim 10,000$ K). Because the main-sequence turnoff (MSTO) mass decreases as age increases, the ZAHB will become bluer as a population ages, assuming all other parameters (e.g., mass loss on the red giant branch, metallicity, helium abundance, etc.) remain fixed. Note that this does not necessarily imply that age is the "second parameter" of HB morphology (e.g., see Sweigart's work in these proceedings). The implied first parameter of the HB morphology debate is metallicity; the HB becomes bluer at lower metallicity, assuming all other parameters (age, mass loss, etc.) remain fixed. This is due to two reasons. First, the MSTO mass at a given age is lower at lower metallicity, because a metal-poor star is more luminous (and thus shorter-lived) than a metal-rich star of the same mass. Second, as the metallicity decreases, the envelope opacity decreases, the star will have a higher $\mathrm{T}_{\mathrm{eff}}$, and the HB becomes bluer. In short, HB morphology tends to become bluer at lower metallicity and higher ages, but other parameters also play a role (rotation, He abundance, deep mixing, etc.), leading to the second parameter debate. Our understanding of the UV upturn is clearly linked to this debate, given the presence of hot HB stars in metal-rich elliptical galaxies.

Because HB morphology is sensitive to age, Greggio & Renzini (1990) noted that the UV upturn should also be very sensitive to age; Bressan, Chiosi, & Fagotto (1994) demonstrated that the UV upturn might even be useful as a diagnostic for determining the ages of old ellipticals. Indeed, using the infall model of chemical evolution, Tantalo et al. (1996) demonstrated that the $1550-V$ color in an old elliptical galaxy spectrum (age $\sim$ 6 Gyr) could change by 4 mag over a timescale of a few Gyr, while other well-studied colors ($V-K$, $V-J$, $B-V$, $V-R$, $U-B$, etc.) only change by $\sim$ 0.1 mag on the same timescale. Unfortunately, the many parameters that govern HB morphology remain poorly constrained, and thus this age diagnostic has yet to be calibrated.

## 2. HUT Observations

In 1990 and 1995, the Hopkins Ultraviolet Telescope (HUT) observed six quiescent local elliptical galaxies as part of the Astro-1 and Astro-2 Space Shuttle missions (see Davidsen et al. 1992 for a description of the instrument and its capabilities). These galaxies – NGC1399, M60, M89, M49, NGC3115, and NGC3379 – span a wide range of UV upturn strength ($2.05 \leq 1550-V \leq 3.86$), but their far-UV (900–1800 Å) spectral energy distributions (SEDs) are all similar to those of stars with 20,000 K $\leq$ $T_{\rm eff}$ $\leq$ 23,000 K (Brown, Ferguson, & Davidsen 1995). The data are inconsistent with ongoing star formation following a normal IMF: there is a lack of CIV absorption, and the flux decreases shortward of 1100 Å (Ferguson et al. 1991). The HUT spectra are not dominated by a population of post-AGB stars, else they would appear much hotter. Furthermore, the fuel-consumption theorem (Greggio & Renzini 1990) relates the stellar evolutionary flux (SEF), also known as the stellar death rate, to the bolometric luminosity within the HUT aperture; this constraint means that the relatively short-lived post-AGB stars cannot produce the magnitude of flux observed by HUT. However, the HUT spectra are consistent with the integrated light of hot HB stars and their descendants. The data demonstrate that a minority population ($\lesssim$ 20% of the SEF) of hot HB stars and their descendants can produce the far-UV light, with a small contribution from the remaining stars that evolve along post-AGB tracks (Brown et al. 1997).

## 3. Ultraviolet Imaging of M32

M32 is usually considered a "compact elliptical" instead of a dwarf elliptical (see Da Costa 1997 and references therein), and as such it is the closest example of a true elliptical galaxy. Given its proximity, we can resolve the hot population in the core of the galaxy with the HST. Several programs have used the Faint Object Camera (FOC) toward this end, prior to and after refurbishment of the HST (see Brown et al. 1998b and references therein). Brown et al. (1998b) resolved 183 stars in the center of M32; the colors and luminosities of these stars placed them in the AGB-Manqué and post-early-AGB evolutionary phases. Although these UV observations were not deep enough to resolve the hot HB, they did imply that the Space Telescope Imaging Spectrograph (STIS) could achieve this goal in a reasonable allocation of observing time.

In October 1998, the STIS observed a $25'' \times 25''$ field, centered $7.7''$ from the M32 core, using the near-UV detector (NUV-MAMA with F25QTZ filter), for 23 ksec. The relatively large throughput of the bandpass, combined with the lack of red leak, allowed the detection of 8000 hot HB and post-HB stars in the center of M32. Photometric reduction was done via PSF-fitting with the DAOPHOT package (Stetson 1987); the stars were placed on the STMAG photometric standard, where a flat $F_\lambda$ spectrum of 1 erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ corresponds to $-21.1$ mag. In the STMAG magnitude system, the stars in our photometric catalog span a range of 21–28 mag; in the deepest parts of the image, the catalog is reasonably complete ($> 25\%$) to 27 mag. The hot HB spans a range of 25–27 mag at $T_{\rm eff} > 8500$ K, and thus these images are sufficiently deep for photometry on the hot HB. We have calculated a set of solar-metallicity HB and post-HB evolutionary tracks for comparison with the STIS data.

Although the analysis of the data is in progress, the southwest half of the image, a section that ranges $8$–$20''$ from the center of the galaxy, is sufficiently deep and uncrowded to allow a preliminary investigation of the evolved population. In that region, the uncorrected STIS luminosity function ranges from $\sim 10$ stars per 0.5 mag bin at 22–24 mag, and increases to hundreds of stars per bin at magnitudes fainter than 25. Including a completeness correction, there are over a thousand stars per bin near 27 mag.

Post-AGB stars alone cannot produce such a luminosity function, if they evolve in the manner described by the H-burning and He-burning tracks found in the literature (e.g., Schönberner 1987; Vassiliadis & Wood 1994). In this portion of the STIS image, the bolometric luminosity can be determined from the extant optical data, a bolometric correction of $-0.875$ mag (Worthey 1994), an extinction correction assuming $E(B-V) = 0.11$ (Ferguson & Davidsen 1993), and a distance modulus of 24.43 mag. The fuel consumption theorem (Greggio & Renzini 1990) relates the bolometric luminosity to the stellar evolutionary flux: SEF$= 2.2 \times 10^{-11}$ stars yr$^{-1} L_\odot^{-1}$ $= 8.62 \times 10^{-4}$ stars yr$^{-1}$. Even with all of these stars evolving through a given post-AGB channel, the post-AGB tracks with mass larger than 0.6 $M_\odot$ evolve rapidly, and would only produce a tiny fraction of the stars in the STIS image. The slowest tracks, such as the 0.546 $M_\odot$ track of Schönberner (1987), actually present two problems. First, they produce dozens of stars per 0.5 mag bin at $21 \leq$ STMAG $\leq 24$ mag, which are many more than observed by STIS. Second, this track also produces dozens of stars per bin at $24 \leq$ STMAG $\leq 28$ mag, where STIS observed an order of magnitude more, even without correcting for completeness. Because the post-AGB stars in this old population are presumably evolving along low-mass tracks, the lack of bright stars in the STIS image may be an indication that the post-AGB transition from the AGB to the later and hotter phases ($T_{\rm eff} > 60,000$ K) occurs on much more rapid timescales than those expected from the canonical tracks, or is dust-enshrouded (see, e.g., Käufl, Renzini, & Stanghellini, 1993).

In contrast, the presence of hot HB stars and their progeny easily reproduces the large number of faint stars seen by STIS. If $\sim 5\%$ of the SEF passes through the hot HB, the resulting luminosity function is in close agreement with the STIS data, over the entire range of observed magnitudes. The resulting UV spectrum from such a population agrees with the weak UV flux measured by IUE (Burstein et al. 1988). Given the small fraction of the population entering the hot HB, we must conclude that the vast majority of the population passes through the red HB phase and the subsequent post-AGB evolution. So, although a small population of hot HB stars can explain the stars present in the STIS image, we still must explain the lack of bright stars. The post-AGB stars must either be evolving along more massive (and thus more rapidly evolving) tracks, the transition time from the AGB to the hotter post-AGB phases must be more rapid than that expected from the canonical low-mass tracks, or this transition must be enshrouded in circumstellar dust. Whichever the case, the contribution of post-AGB stars to the STIS luminosity function would be small. Note that very young ages ($\lesssim 1$ Gyr) are required to produce main sequence stars brighter than the HB, and so the STIS image is dominated by an old population.

The STIS image convincingly demonstrates that the weak UV upturn in M32 comes from a small population of hot HB stars and their descendants. Prior to these data, the weak UV upturn in M32 could have been explained by low-mass post-AGB stars alone, without violating fuel consumption constraints on the SEF. Far-UV imaging of the same field with STIS would be useful to provide color information for these stars. Colors would further constrain the HB morphology, and provide clues to the post-AGB evolution, because post-AGB stars presumably contribute a small but significant fraction of stars to the STIS luminosity function.

## 4. Measurements of the UV Upturn in Abell 370

The UV upturn is thought to evolve rapidly as a population ages. Some groups (e.g., Yi et al. 1999) have predicted a rapid decline in UV upturn strength at increasing redshift; others (e.g. Tantalo et al. 1996) predict that the UV upturn should show a strong increase at intermediate ages ($\sim 6$ Gyr), followed by a period where it is approximately constant. In this latter scenario, the amount of fading expected at higher redshifts depends upon the formation redshift of the elliptical galaxy in question. Several previous attempts to measure the UV upturn at intermediate redshifts, using UV imaging and spectroscopy with the HST, have been inconclusive (e.g., Windhorst et al. 1994; Renzini 1996; Buson et al. 1998).

The FOC can observe with two long-pass filters that are appropriate for observations of the UV upturn at intermediate redshift. Specifically, the F130LP and F370LP filters provide a discriminator between flux longward and shortward of 3700 Å, corresponding to a rest-frame wavelength of 2500–2700 Å in the redshift range 1.48–1.37. This rest-frame wavelength represents the spectral division between the hot evolved populations that produce the far-UV flux and the cooler RGB, AGB, and MSTO populations responsible for the $V$-band flux. We have obtained FOC measurements of four ellipticals in the galaxy cluster Abell 370, at $z = 0.375$, to measure the UV upturn at a lookback time of $\sim 4$ Gyr (Brown et al. 1998a).

Abell 370 is a well-studied galaxy cluster. The four ellipticals in our analysis (BO# 10, 24A, 24B, & 34; Butcher, Oemler, & Wells 1983) have all been observed spectroscopically from the ground (Soucail et al. 1988); these spectra confirm their cluster membership, are consistent with passively-evolving old populations, and show no evidence of star formation (e.g., from [OII]). Their $U - V$ colors are also consistent with passive evolution (MacLaren, Ellis, & Couch 1988). Morphological classification is confirmed by WFPC (Couch et al. 1994) and WFPC2 (HST GO program 6003) imaging.

We performed aperture photometry upon these four cluster ellipticals, using two aperture sizes: 65 pixels (0.91″) and 12 pixels (0.17″). The large aperture includes all of the light detected by the FOC; the smaller aperture gives a measurement of the core light, and may be more appropriate for comparison to measurements of the UV upturn in local ellipticals, which were done with IUE. Local ellipticals usually show a weaker UV upturn at increasing radius (Ohl et al. 1998). We show our measured flux ratios in Table 1. Exposure times varied from 2800–8500 sec, and so our counting statistics are quite good.

Table 1. FOC Photometry and Model Predictions

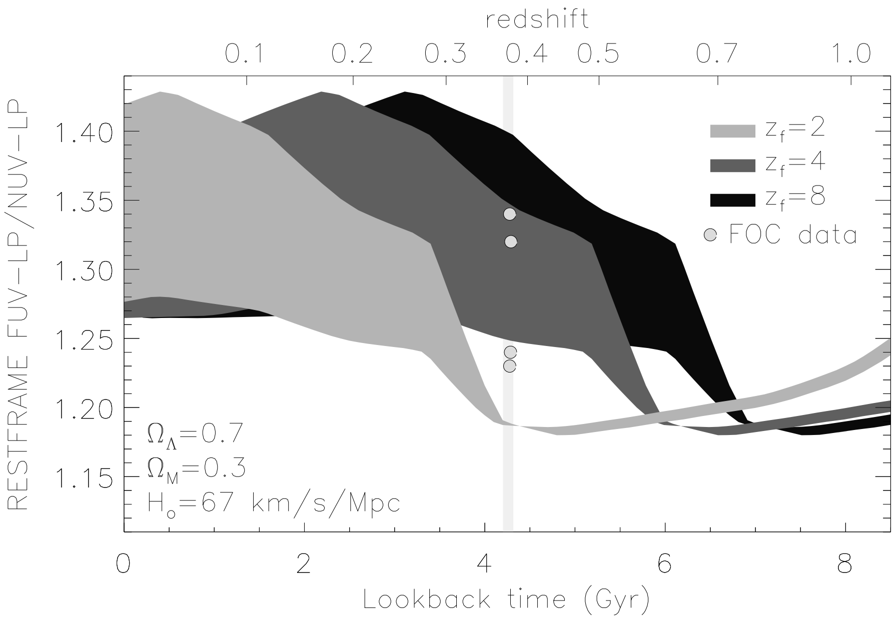
| Galaxy | F130LP (cts s$^{-1}$) | F370LP (cts s$^{-1}$) | F130LP/F370LP | rest-frame $1550 - V$ (mag) |
|---|---|---|---|---|
| Photometry: large aperture | | | | |
| BOW #10 | 9.03 | 6.82 | 1.32 | 3.0 |
| BOW #24a | 4.55 | 3.69 | 1.23 | 3.4 |
| BOW #24b | 4.22 | 3.14 | 1.34 | 2.9 |
| BOW #34 | 7.13 | 5.75 | 1.24 | 3.4 |
| Photometry: nuclear aperture | | | | |
| BOW #10 | 1.78 | 1.21 | 1.47 | 2.2 |
| BOW #24a | 0.841 | 0.650 | 1.29 | 3.1 |
| BOW #24b | 1.11 | 0.840 | 1.32 | 2.9 |
| BOW #34 | 1.48 | 1.16 | 1.28 | 3.2 |
| Redshifted non-evolving templates: nuclear aperture | | | | |
| NGC 1399 | 1.55 | 1.02 | 1.52 | 2.05 |
| M 60 | 1.26 | 0.856 | 1.47 | 2.24 |
| M 49 | 1.22 | 0.995 | 1.23 | 3.42 |

To determine the relationship between rest-frame $1550 - V$ color and the F130LP/F370LP flux ratio at this redshift, we first compared our data to the spectra of local galaxies. After redshifting the spectra of three local ellipticals (M49, M60, and NGC1399) to $z = 0.375$, we used the IRAF/synphot/calcphot package to predict the F130LP/F370LP flux ratio that would be observed for these local galaxies, if they were members of Abell 370. The predictions are shown in Table 1. As the table demonstrates, in a large aperture, the Abell 370 ellipticals all show a UV upturn at least as strong as that seen in M49. In a nuclear aperture, three of these four ellipticals show even stronger UV upturn colors, with one as strong as that in M60.

Comparison to the redshifted spectra of local ellipticals assumes a non-evolving template for the interpretation. However, the main sequence turnoff becomes bluer and brighter at decreasing age, and so we also compare our measurements with the predictions for an evolving elliptical galaxy. Tantalo et al. (1996) computed the SEDs of elliptical galaxies as a function of age, assuming a range of galaxy masses, with chemical evolution following the infall model.

In their models, the rise of the UV upturn occurs at $\sim 6$ Gyr, but note that the actual age of this occurrence may vary by several Gyr, depending upon the assumptions made regarding mass loss, $\Delta Y/\Delta Z$, and details regarding the chemical evolution. The observed F130LP/F370LP flux ratio translates to a rest-frame FUV-LP/NUV-LP flux ratio at $z = 0.375$, and so we calculated this rest-frame flux ratio as a function of age for the two most massive models in the Tantalo et al. (1996) set: $3 \times 10^{12}\ M_{\odot}$ and $1 \times 10^{12}\ M_{\odot}$. The range of FUV-LP/NUV-LP flux ratio spanned by these models is shown in Figure 1, plotted as a function of lookback time and redshift, for three different formation redshifts (2, 4, and 8).

Figure 1. The evolution of the UV upturn as a function of redshift, as characterized by the rest-frame FUV-LP/NUV-LP flux ratio in the SEDs of Tantalo et al. (1996) for giant ellipticals. This flux ratio corresponds to the observed FOC F130LP/F370LP ratio for observations at $z = 0.375$, the redshift of Abell 370. Our large-aperture measurements for Abell 370 (circles) show no evidence of evolution in the UV upturn between a lookback time of 4 Gyr and today, implying a high formation redshift ($z > 4$).




Although our understanding of the UV upturn and HB morphology is not sufficient to allow its use as an accurate age indicator, it is interesting to consider the implications of our FOC measurements, under the assumption that the Tantalo et al. (1996) models are correct. In the given cosmology, the ellipticals in Abell 370 would have formed at $z > 4$ in order to demonstrate such strong UV upturn colors. For $\Omega_\Lambda = 0$ and $\Omega_M = 0.1$, the implied formation redshift is not significantly changed; for $\Omega_\Lambda = 0$ and $\Omega_M = 0.3$, the implied formation redshift is higher. If the Abell 370 ellipticals and the local population of ellipticals both formed at a common redshift $z \geq 4$, the lack of evolution seen in the UV upturn can be understood as evidence that both epochs are on the "flat" portion of the UV upturn evolutionary curves, after the UV upturn has leveled off.

Note that a small amount of star formation is sufficient to produce a significant UV upturn in these galaxies. Although these ellipticals appear to be passively evolving, less than 0.1 $M_\odot$ yr$^{-1}$ of star formation would be enough to produce the UV upturn we observe (see Madau, Pozzetti, & Dickinson 1998); this level of star formation is slightly below the constraints available from the extant data.

Our measurements provide a first step in mapping the evolution of the UV upturn with lookback time. Further observations are clearly needed to rule out star formation as the source of the UV emission in these high redshift galaxies, and to trace the evolution to both higher and lower redshifts. HST Observations of a cluster at $z = 0.55$ are planned in the near future (GTO program #8020). Unless the redshift of formation is very high, these galaxies ought to be very faint in the far-UV. Once the UV upturn is measured in a statistically significant number of galaxies over a range of redshifts, the evolution can be determined independent of star formation contamination. It would be unlikely that small levels of star formation could be synchronized within clusters and change as a function of redshift to mimic the UV upturn evolution.

## 5. Summary

The UV upturn provides a sensitive tracer of age in old populations, and can potentially constrain the evolutionary history of ellipticals with a diagnostic that is independent of those used at longer wavelengths. Spectra and photometry of local ellipticals confirm that hot HB stars are responsible for the UV upturn, and so the calibration of the UV upturn as an age diagnostic will depend upon a better understanding of the mechanisms driving HB morphology (e.g., RGB mass loss). Measurements of the UV upturn at a series of redshifts should provide insight into the chemical evolution of galaxies and the production of hot HB stars in metal-rich populations, with the eventual goal of constraining the formation history of ellipticals.

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